Standard test methods and data for evaluating fire resistive structural steel

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WTC investigation revealed two research areas:

(1) High-temperature deformation data for modern US construction steels do not exist.

Objective: Produce a validated database of mechanical properties for several common construction steels.
Method: High-T tensile and creep of ordinary and FR steels.

(2) No standard definition of fire resistance, as applied to structural steel (as opposed to fire resistance of components or assemblies) currently exists.

Objective: Develop and standardize a test method for evaluating the fire resistance of structural steel.
Method: Compare two different methods using the steels characterized above.

Steel stress-strain behavior

Eurocode model

Engineering stress, MPa (y-axis: 0, 100, 200, 300, 400)

$f_{amax,20}$

$f_{ap,20}$ = proportional limit

ε_{amax}

Engineering strain (x-axis: 0.00, 0.01, 0.02, 0.03, 0.04, 0.05)

Typical stress-strain data

yield point elongation

Yield point, YP

0.002 offset

yield strength, YS

Engineering stress, MPa (y-axis: 0, 100, 200, 300, 400)

Engineering strain (x-axis: 0.00, 0.01, 0.02, 0.03, 0.04, 0.05)

General Approach

Create high-T curves by appropriate scaling of RT curves.
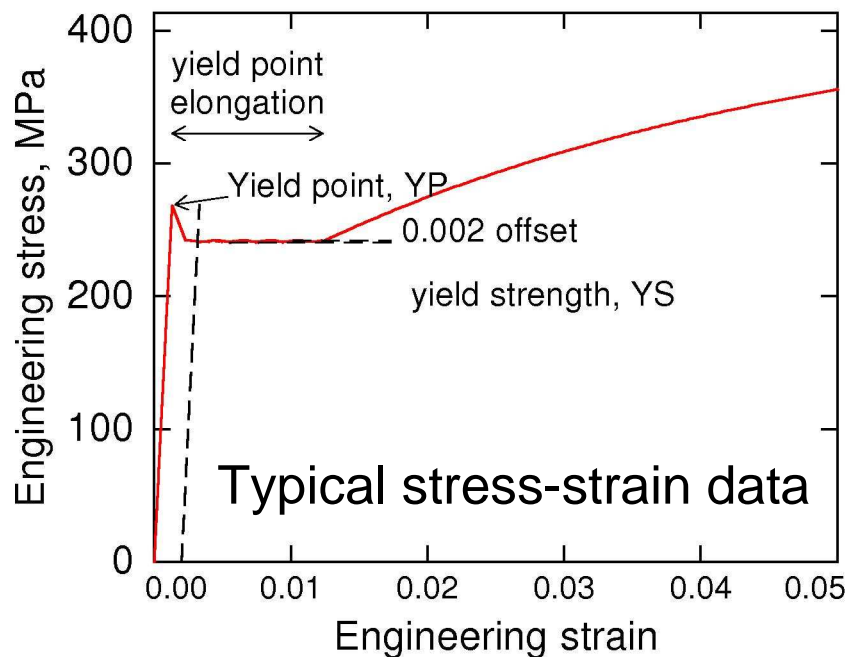
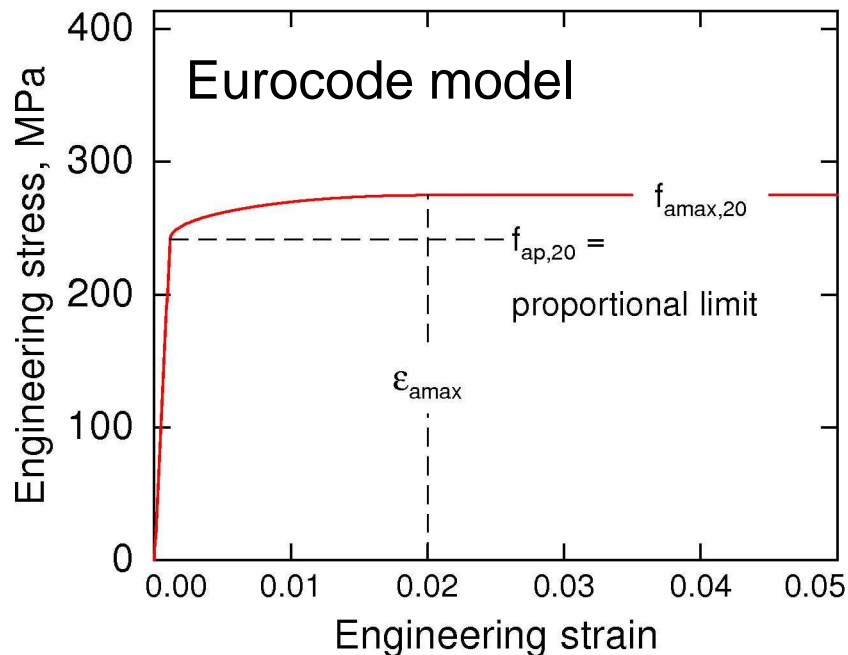Example: Eurocode: $f_{amax}(T)$, $f_{ap}(T)$, FY

Produce stress-strain behavior for input into finite element models (FEM).
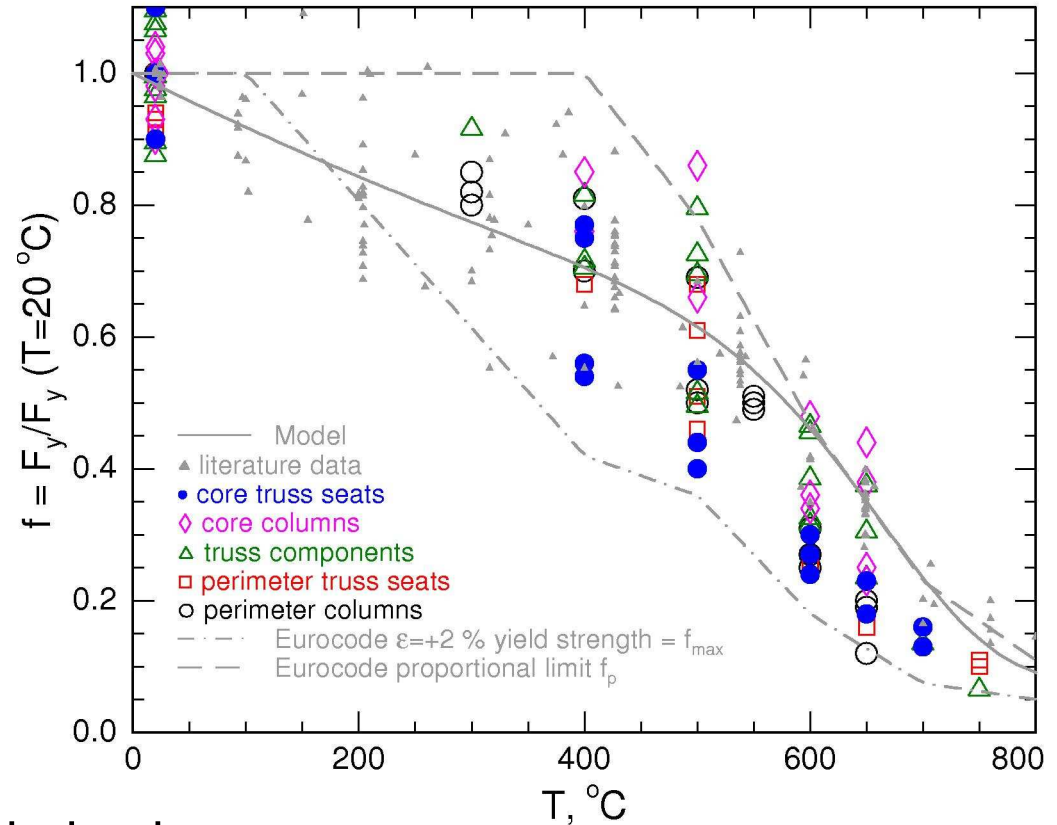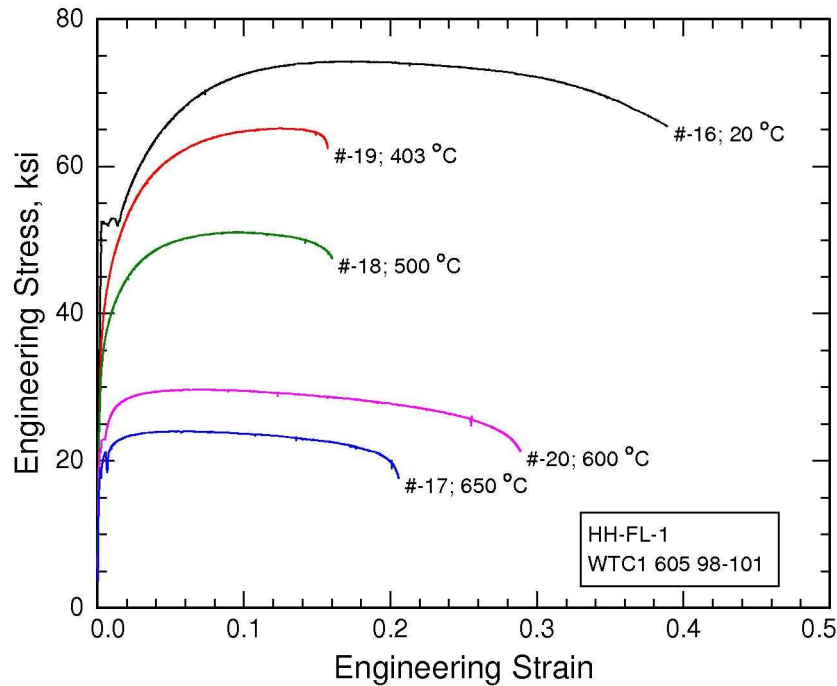
Express data in useful formats.

Creep

High-T stress-strain behavior implicitly contains creep (through strain rate)

On-going work, but a different presentation.
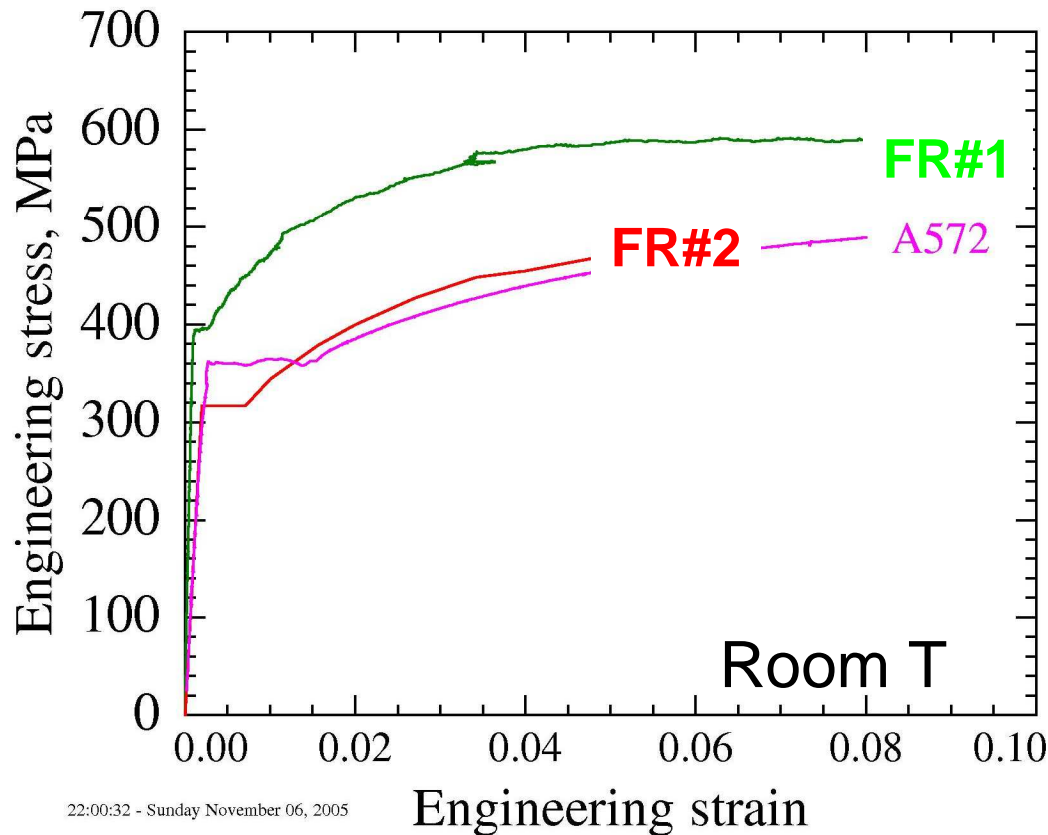
Steel at high temperature

$T<500$ °C: time-independent behavior

$T>500$ °C: time- *dependent* behavior (not captured by simple models)

Current codes: "steel is steel"

2 "FR" and 1 ordinary structural steels

FR steels are intended as "drop-in" replacements for existing structural steels, but possess enhanced high-temperature capability
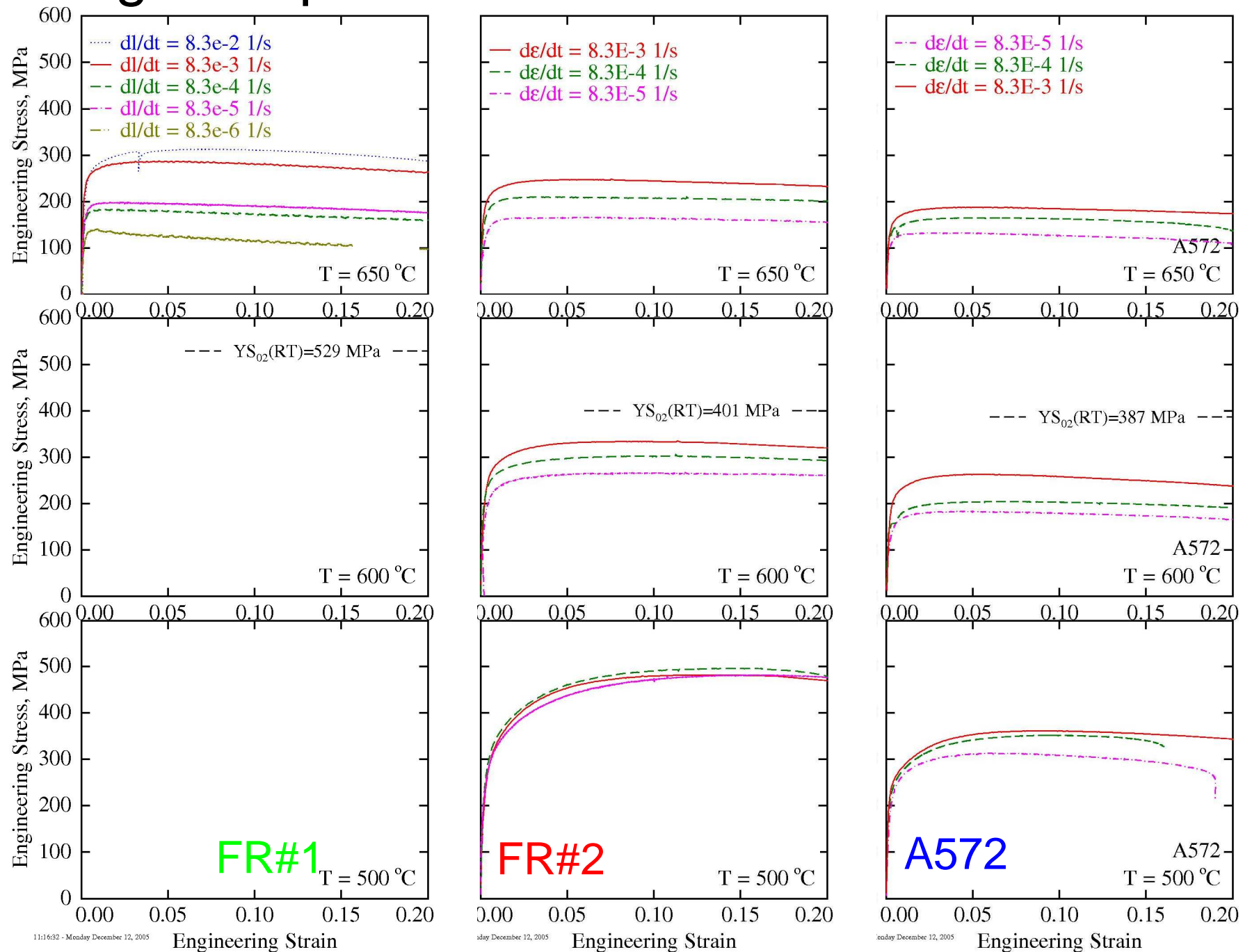
Translates to added time before failure in fire

Engineering stress, MPa vs Engineering strain

- FR#1
- FR#2
- A572
- Room T

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FR#1
Fy   = 407 MPa
Fy02 = 539 MPa

FR#2
Fy   = 318 MPa
Fy02 = 401 MPa

A572
Fy   = 359 MPa
Fy02 = 387 MPa

FR#1:   0.08C 1.3Mn 0.65Mo 0.03Nb 0.02Cr
FR#2:   0.11C 1.0Mn 0.30Mo 0.03V   0.7Cr
A572:   0.17C 1.1Mn 0.00Mo 0.06V   0.2 Cu

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High-temperature stress-strain behavior

Figure panels (3×3 grid of engineering stress vs. engineering strain plots):

Top-left panel (T = 650 °C):
- dl/dt = 8.3e-2 1/s
- dl/dt = 8.3e-3 1/s
- dl/dt = 8.3e-4 1/s
- dl/dt = 8.3e-5 1/s
- dl/dt = 8.3e-6 1/s

Top-middle panel (T = 650 °C):
- $d\varepsilon/dt$ = 8.3E-3 1/s
- $d\varepsilon/dt$ = 8.3E-4 1/s
- $d\varepsilon/dt$ = 8.3E-5 1/s

Top-right panel (T = 650 °C, A572):
- $d\varepsilon/dt$ = 8.3E-5 1/s
- $d\varepsilon/dt$ = 8.3E-4 1/s
- $d\varepsilon/dt$ = 8.3E-3 1/s

Middle-left panel (T = 600 °C): $YS_{02}(RT)=529$ MPa

Middle-middle panel (T = 600 °C): $YS_{02}(RT)=401$ MPa

Middle-right panel (T = 600 °C, A572): $YS_{02}(RT)=387$ MPa

Bottom-left panel (T = 500 °C): FR#1

Bottom-middle panel (T = 500 °C): FR#2

Bottom-right panel (T = 500 °C, A572): A572
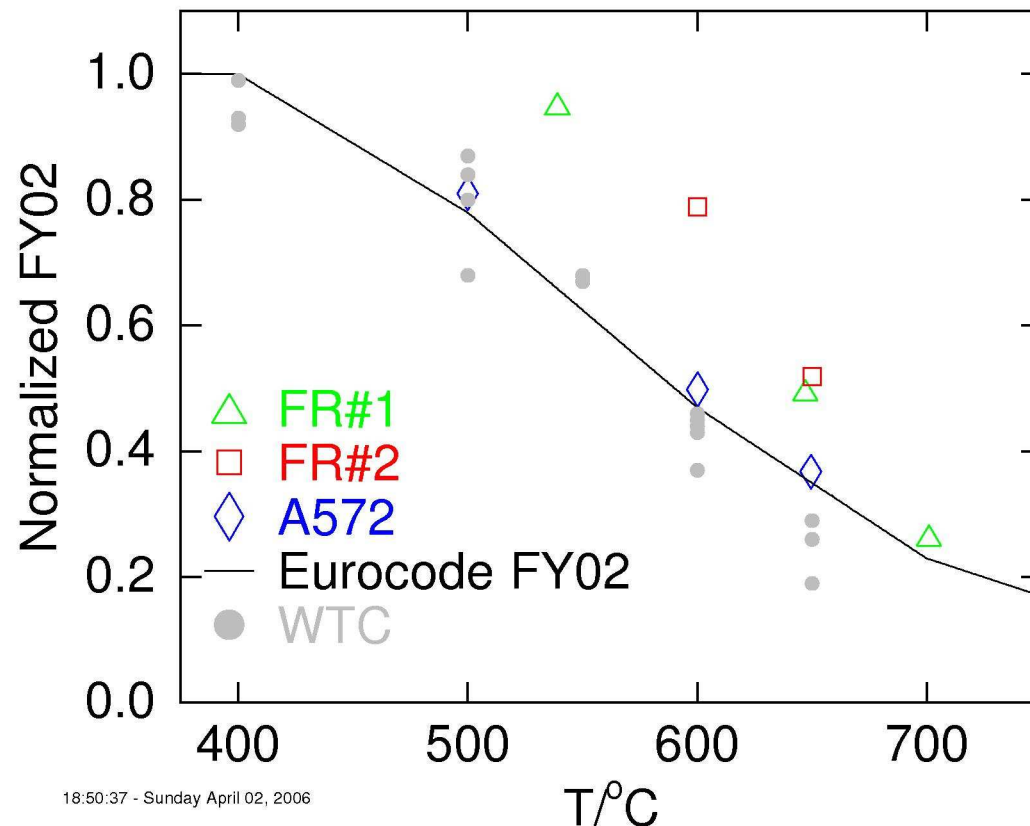
Axis labels: Engineering Stress, MPa (y-axis); Engineering Strain (x-axis)

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High temperature tensile behavior

Normalized FY02:
Ratio of high-temperature 2 % proof strain yield strength to room-temperature 0.2 % offset yield strength.
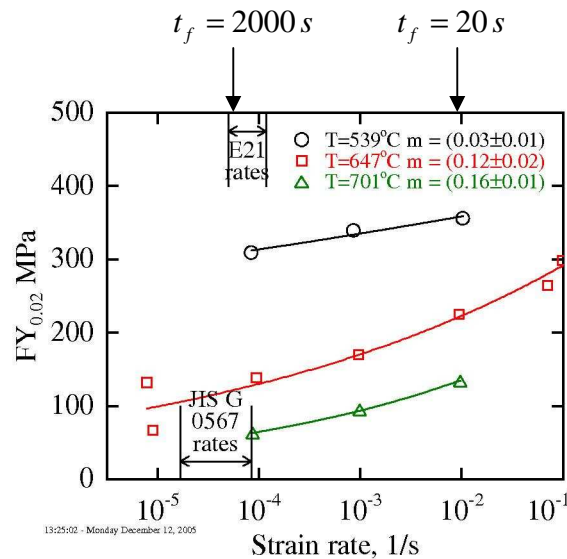
- Many NIST-tested WTC steels lie below Eurocode curve
- Not easy to transform this data into an added time, however.

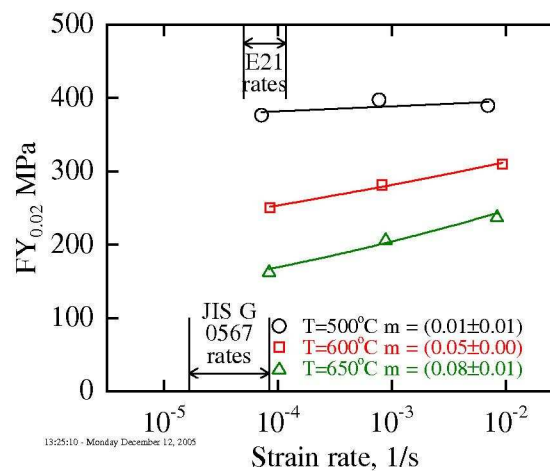$de/dt \sim = 8 \times 10^{-5}$ 1/s (= E 21 rate = 0.005 min^{-1})
E 21 rate corresponds to 5% strain in 600 s

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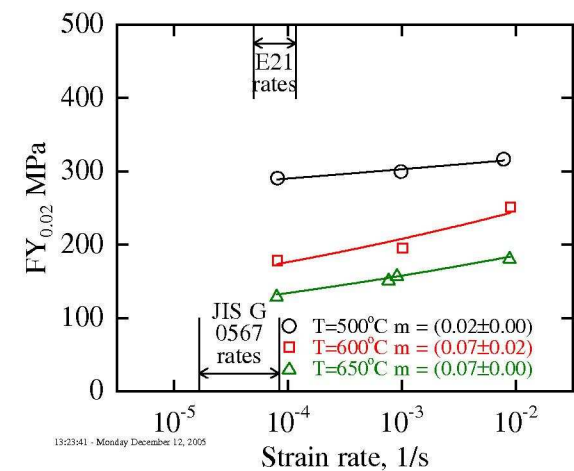# High-temperature strain rate sensitivity

$$\sigma = K\left(\frac{\partial \varepsilon}{\partial t}\right)^{m} \varepsilon^{n}$$

FR#1

FR#2

A572

Strength becomes increasingly sensitive to strain rate for $T > 500\ °C$

Implications for modeling

- Accurate constitutive properties are essential

- Time dependence of strength is important for $T > 500\ °C$

- Steel constitutive law may not be immediately importable into beam or column deformation behavior

Developing a test for fire resistance of steel

- Not ASTM E 119 ! (component test)

- **Purpose** evaluate and rank steels: high-T analogue of the mill test report

- **Requirements:**

  – single test

  – easily implemented

  – robust against experimental variability

  – represents real-world behavior

- **Candidates**

  – High-T tensile (possibly with restrictions on testing rate and definitions)

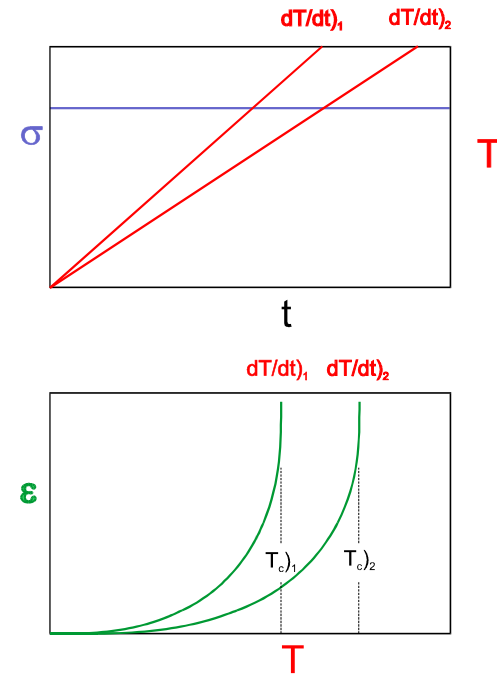 – Temperature ramp test (like E 119)

Three possible definitions of a fire-resistance test
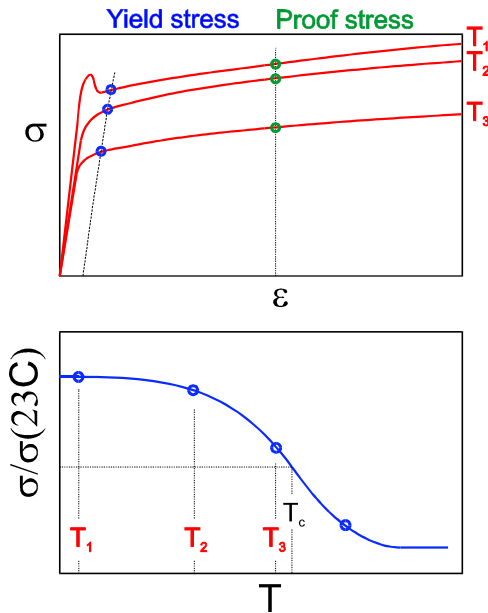
High-T tensile test (E 21)
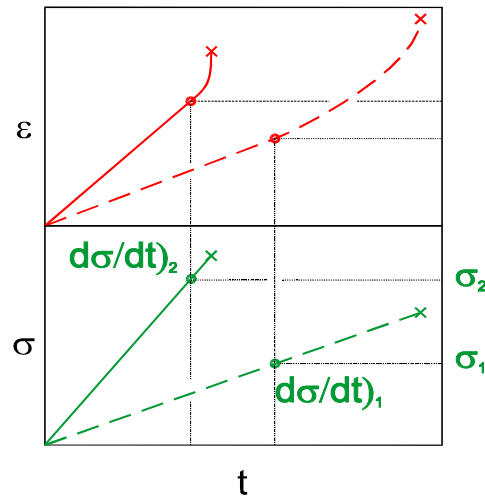
High-T, slow-rate tensile test w/ proof stress

Temperature ramp test

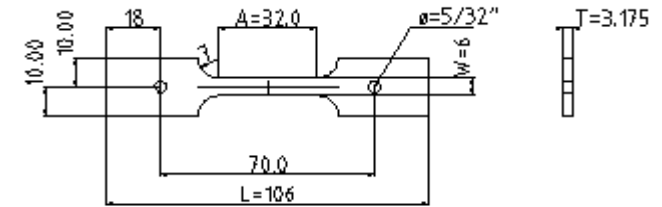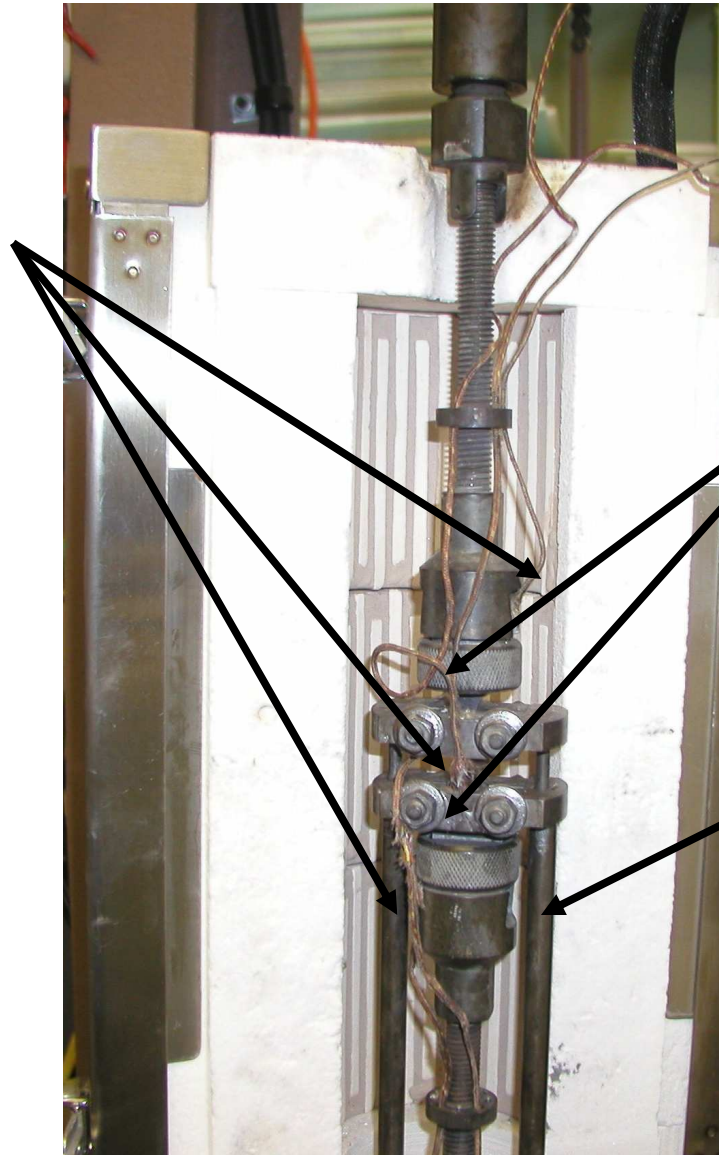| (+)	• Familiar test method • Existing Japanese approach • 2Fy/3 @ 600℃	•Small change to existing approach •Captures t-dependence •Choose $t_f\sim$2h	• Combines T and t effects • Report T_c • Like component (E119) test • "T-programmed creep test"
(-)	• ignores t-dependent effects • loading rate effects are important: 1.6x per decade • definition of yield strength (reason for Eurocode e=0.02)	•Single T may not capture full behavior	•unfamiliar parameter •Can one dT/dt capture all behaviour? •Cannot use data generated in ordinary calculations

FR Ramp Test configuration

3 control
thermocouples
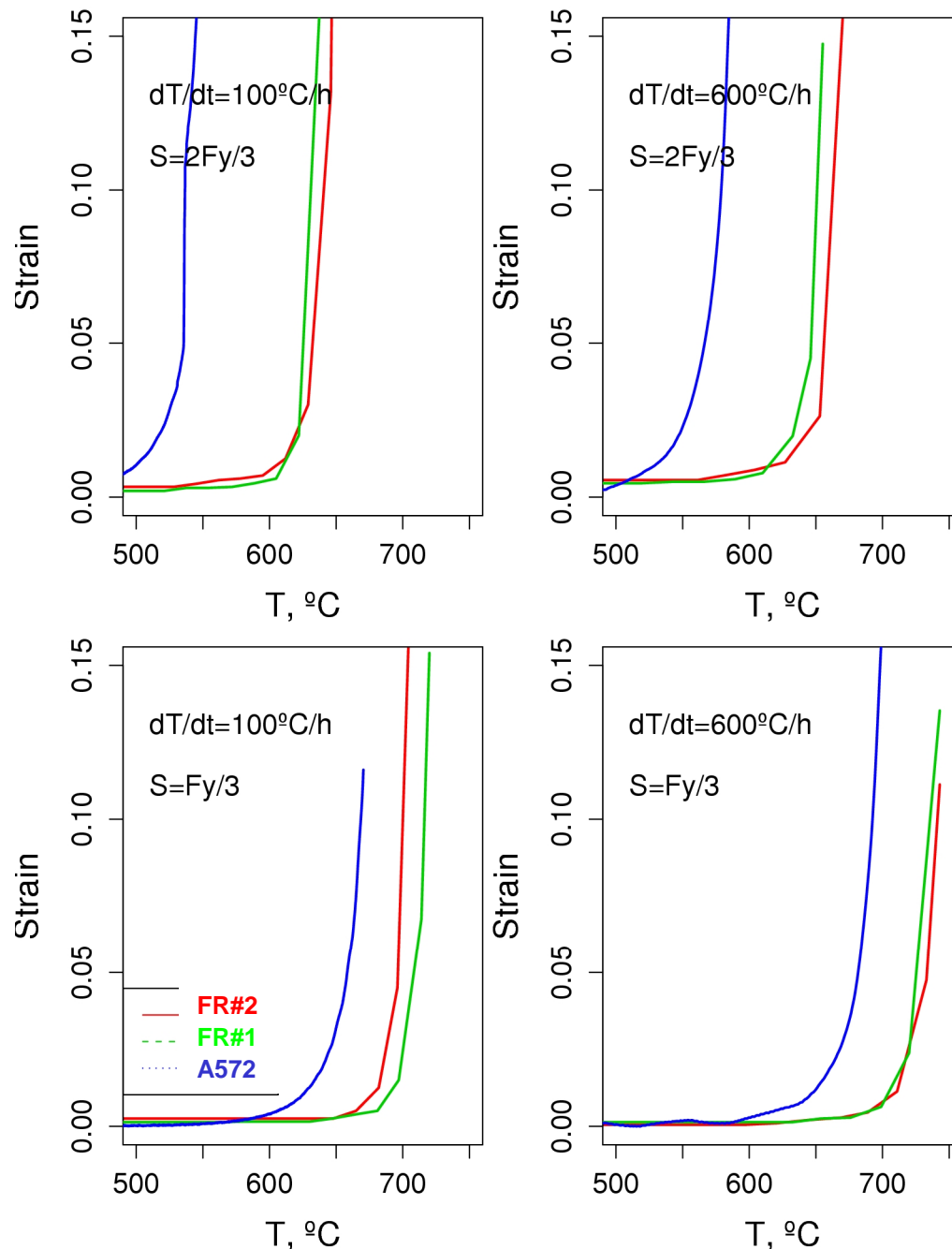
40:1 lever arm
creep frame

3 zone furnace

2 monitor
thermocouples in
contact with
extensometer knife
edges

averaging
extensometer

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FR Ramp test behavior

Test
linear temperature ramp under fixed load expressed as a fraction of RT FY
Failure: e=0.05

Results
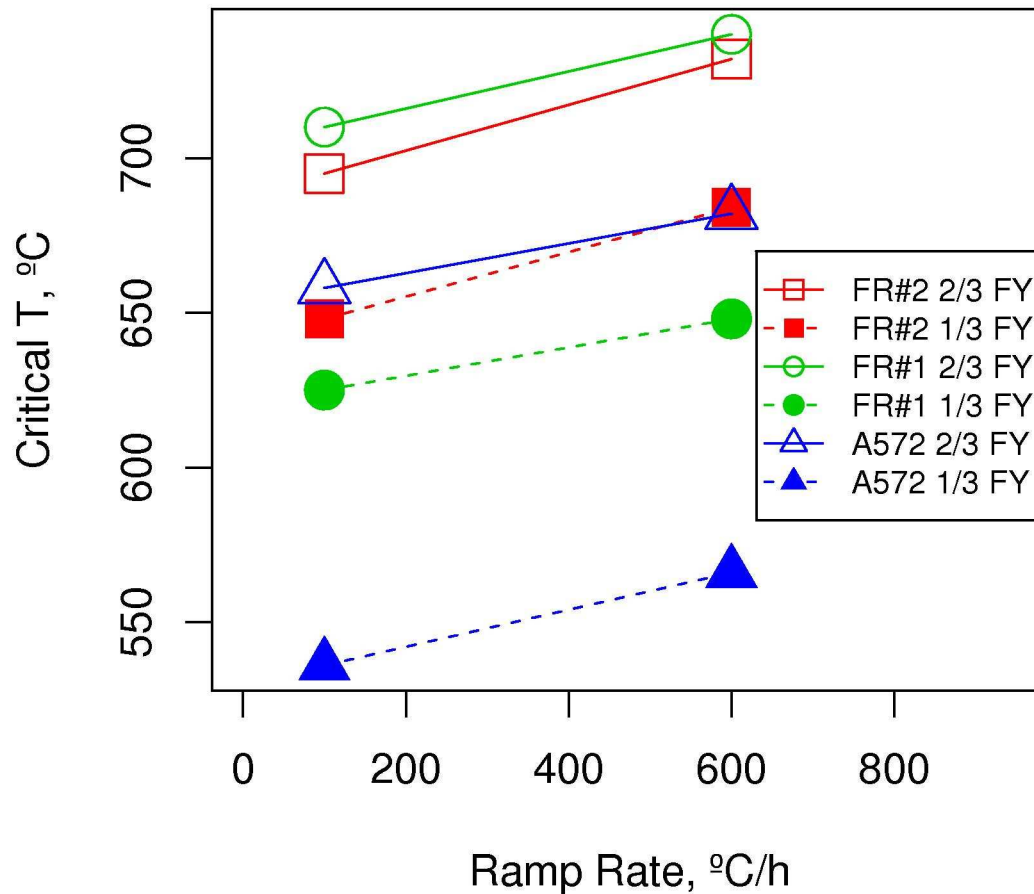
FR#1 & FR#2 are nearly identical

A572 T_c is 50 °C less

Steel	ratio	dT/dt ℃/h	T_c ℃
FR#2	1/3	100	695
FR#2	2/3	100	648
FR#2	1/3	600	732
FR#2	2/3	600	684
FR#1	1/3	100	710
FR#1	2/3	100	625
FR#1	1/3	600	740
FR#1	2/3	600	648
A572	1/3	100	658
A572	2/3	100	536
A572	1/3	600	682
A572	2/3	600	566

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Critical temperature behavior

Note:
- range of ramp rates represents maximum practical range
- reversal of FR steel positions
- FR steels have 40 °C-70 °C advantage over A572

FR test development summary

	Fy002/Fy002 (RT) @ 600 ℃	Fy02/Fy02 (RT) @ 600 ℃	Rank	Tc ℃	Rank
FR#1	~0.53	~0.47	3	710	1
FR#2	0.60	0.71	1	695	2
A572	0.40	0.51	2	658	3

Fy evaluated at E21 rate

Tc evaluated at Fy/3 100℃/h

The two methods do not rank the steels in the same order!

Still to do

- Characterize several other modern construction steels

- Use measured high-T deformation properties to predict temperature ramp test results

- Long-term: use data to predict beam/column deformation